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Massive stars exploding in a He-rich circumstellar medium – I. Type Ibn (SN 2006jc-like) events

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ABSTRACT

We present new spectroscopic and photometric data of the Type Ibn supernovae 2006jc, 2000er and 2002ao. We discuss the general properties of this recently proposed supernova family, which also includes SN 1999cq. The early-time monitoring of SN 2000er traces the evolution of this class of objects during the first few days after the shock breakout. An overall similarity in the photometric and spectroscopic evolution is found among the members of this group, which would be unexpected if the energy in these core-collapse events was dominated by the interaction between supernova ejecta and circumstellar medium. Type Ibn supernovae appear to be rather normal Type Ib/c supernova explosions which occur within a He-rich circumstellar environment. SNe Ibn are therefore likely produced by the explosion of Wolf–Rayet progenitors still embedded in the He-rich material lost by the star in recent mass-loss episodes, which resemble known luminous blue variable eruptions. The evolved Wolf–Rayet star could either result from the evolution of a very massive star or be the more evolved member of a massive binary system. We also suggest that there are a number of arguments in favour of

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a Type Ibn classification for the historical SN 1885A (S-Andromedae), previously considered as an anomalous Type Ia event with some resemblance to SN 1991bg.

Key words: supernovae: general – supernovae: individual: SN 2006jc – supernovae: individual: SN 1999cq – supernovae: individual: SN 2000er – supernovae: individual: SN 2002ao – supernovae: individual: SN 1885A.

1 INTRODUCTION

The most massive stars, i.e. those with initial masses larger than 30 $M_{\odot}$, are thought to end their lives with the core-collapse explosion of a Wolf–Rayet (WR) star. Before this stage, many of them undergo a short period of instability called the luminous blue variable (LBV) phase. This phase probably lasts of the order of 10^4–10^5 yr (Maeder & Meynet 1987; Humphreys & Davison 1994; Bohannan 1997; Vink & de Koter 2002; Smith 2008), during which LBVs lose mass through recurrent mass-loss episodes. Most LBVs undergo fairly minor variability (typically below 1 mag) which is commonly called the S Doradus phase. But occasionally LBVs experience giant outbursts in which their luminosity rapidly increases and they can reach absolute visual magnitudes around −14 (Davidson & Humphreys 1997; Maund et al. 2005; Van Dyk et al. 2006), accompanied by the ejection of a large portion of their hydrogen envelope (Smith & Owocki 2006). An overview of our current knowledge of LBVs can be found in Van der Genderen (2001). At the time of explosion, which is expected to occur a few $\times 10^5$ yr after the last major LBV outburst (see e.g. Heger et al. 2003; Eldridge & Tout 2004), the mass of the WR star is expected to be of the order of 15–20 $M_{\odot}$. These stars may eventually explode as Type Ib supernovae (SNe Ib) if they have lost the whole H envelope, or as Type Ic supernovae (SNe Ic) if the stars are also stripped of their He mantles (for a comprehensive description of the different SN Types see Filippenko 1997; Turatto et al. 2007).

However, recent work (Kotak & Vink 2006; Smith et al. 2007; Gal-Yam et al. 2007) has suggested the possibility that some very massive stars may explode already *during* the LBV phase, producing luminous supernovae (SNe). Previously, a post-LBV channel was proposed by Salamanca, Terlevich & Tenorio-Tagle (2002) to explain the observed properties of the Type IIn SN 1997eg. In the proposed scenario, LBVs may eventually produce SNe which show high luminosity, blue colour, narrow Hα line in emission, and very slow spectrophotometric evolution. Their spectra are dominated by very narrow ($\lesssim$1000 km s^{-1}), prominent H emission lines which sometimes show complex, multicomponent profiles. These objects would therefore belong to the so-called *Type IIn* SN class (Schlegel 1990). The observed properties of these events are consistent with a scenario in which a significant fraction of the kinetic energy of the SN ejecta is converted into radiation via interaction with a dense, H-rich circumstellar medium (CSM).

A new clue for the death of the most massive stars has recently been proposed for the explosion of the peculiar SN 2006jc (Itagaki et al. 2006; Foley et al. 2007; Pastorello et al. 2007a; Mattila et al. 2008; Smith, Foley & Filippenko 2008; Tominaga et al. 2007). Extensive data sets spanning many wavelength regions have been also presented by Anupama et al. (in preparation), Di Carlo et al. (2007), Immler et al. (2008) and Sakon et al. (2007). Pastorello et al. (2007a) showed the amazing discovery that a major outburst, reaching $M_R = -14.1$ (i.e. an absolute magnitude which is comparable to that of LBV eruptions), occurred only two years before the explosion of SN 2006jc at exactly the same position as the SN and inferred that the two events must be physically related. The physical connection between the two transients is supported by analysis of the SN spectra. These are indeed blue and dominated by relatively narrow ($\sim$2200 km s^{-1}) He I lines in emission (hence the new classification as *Type Ibn*, Pastorello et al. 2007a), likely indicating a Type Ib/c SN embedded within a dense, massive He-rich envelope. Unlike SNe IIn, the photometric evolution of this object is extremely rapid, while the spectra do not change as quickly as the luminosity. The best studied object of this Type is SN 2006jc, but three additional events which appear to be spectroscopically rather similar have been found: SNe 1999cq, 2000er and 2002ao (discovered by Modjaz & Li 1999; Chassagne 2000; Martin et al. 2002, respectively). Foley et al. (2007) first proposed that 2006jc-like events may constitute a distinct class of core-collapse SNe exploding in a He-rich CSM. SN 2005la (Puckett et al. 2005) is also a somewhat similar SN, although with some unique properties. One might reasonably consider it as intermediate between a Type Ibn and a Type IIn event (see Pastorello et al. 2008).

This article is the first of a series of three papers (together with Mattila et al. 2008; Pastorello et al. 2008) in which we will discuss some peculiar, transitional events possibly produced by the explosions of very massive stars. In this paper we will focus on the properties of the four objects which belong to the Type Ibn SN family. Some of the data analysed in this paper have already been published (Matheson et al. 2000; Foley et al. 2007; Pastorello et al. 2007a), others have never been shown before. For SN 1999cq we do not present new data, but we consider only those of Matheson et al. (2000). The aforementioned SN 2005la, which has even more peculiar characteristics, will be analysed separately (Pastorello et al. 2008).

The paper is organized as follows. In Section 2 the properties of the host galaxies of the SN sample are introduced, including reddening and distance estimates. Spectroscopic and photometric observations are presented in Sections 3 and 4, respectively. The quasi-bolometric light curve of SN 2006jc is presented in Section 4.1, while the parameters derived from the bolometric light-curve modelling are discussed in Section 4.2. In Section 5 we examine two different plausible scenarios for the progenitors of SN 2006jc and similar events, while in Section 6 we estimate the frequency of Type Ibn events. Finally, a short summary is given in Section 7.

2 SUPERNOVAE Ibn AND THEIR HOST GALAXIES

All four objects forming the sample of SNe Ibn analysed in this paper exploded in spiral galaxies, but showing different characteristics. While the galaxies hosting SNe 1999cq and 2000er are luminous spirals, both SNe 2002ao and 2006jc are hosted by similarly blue, underluminous (about $M_B \sim -16.0$ and -18.3 for UGC 9299 and UGC 4904, respectively), barred spiral galaxies.

Using a luminosity–metallicity relation (Tremonti et al. 2004), Prieto, Stanek & Beacom (2008) find that the host galaxies of SNe 2002ao and 2006jc are rather metal-poor. On their scale (they adopt the solar oxygen abundance of 12 + log (O/H) = 8.86 dex of

Delahaye & Pinsonneault 2006), the oxygen abundance of these faint galaxies is 12 + log (O/H) ∼ 8.5 dex. However, we should bear in mind that the absolute values of chemical abundances based on nebular lines vary by as much as 0.5 dex depending on the calibration (Bresolin 2007), hence when using the Prieto et al. (2008) values we should relate them to their likely Milky Way solar type abundances. If we assume an absolute magnitude of −21 for the Milky Way their 'solar abundance' would be 9.0 ± 0.2 dex. This would suggest that the host galaxies of SNe 2002ao and 2006jc have subsolar metallicity of 0.4 $Z_{\odot}$.

As mentioned above, the galaxies hosting SNe 1999cq (Matheson et al. 2000) and 2000er are significantly different, being both very luminous ($M_B \sim -21.7$ and −21.4, respectively) spirals. Tremonti et al. (2004) have employed Sloan Digital Sky Survey imaging and spectroscopy of a relatively nearby ($0.005 < z < 0.25$) large sample of star-forming galaxies (about 53 000) and produced an empirical fit between galaxy absolute magnitude and metallicity. Again, despite their absolute scale is still uncertain due to difficulties in calibrating the strong nebular lines (Bresolin 2007), we will adopt this and note the differential abundance between a typical Milky Way solar type value of 9.0 dex and the integrated galaxy abundances. The galaxy, hosting SN 1999cq, UGC 11268, is of Sbc type, with a *B*-band absolute magnitude of −21.7 (according to the LEDA[1] data base). The luminosity–metallicity relation of Tremonti et al. (2004) for this magnitude gives an integrated abundance of 12 + log (O/H) ≈ 9.3 ± 0.2 (dex), significantly higher than those derived for the host galaxies of SNe 2006jc and 2002ao. The metallicity measurements using the relation from Tremonti et al. (2004) might lead to a slight overestimate of the true abundances at the position of SN1999cq because of their selection criteria (see section 7 of Tremonti et al. 2004), and galactocentric position. However, as SN 1999cq lies in the central part of the host galaxy (4.3 arcsec off-centre, i.e. with a deprojected distance of 2.4 kpc from the nucleus) we would expect the metallicity at the SN location not to deviate too much from the global value quoted.

SN 2000er occurred in the edge-on peculiar/interacting Sab ESO 115−G9 galaxy, which has a *B*-band absolute magnitude of −21.4 (LEDA). The Tremonti 2004 relation gives an integrated oxygen abundance 12 + log (O/H) ≈ 9.2 ± 0.2 (dex). Even though early-type spirals have shallow abundance gradients, in this case the effect may not be negligible at the SN distance. Since the host galaxy inclination is close to 90°, adopting a distance of ESO 115−G9 of about 130 Mpc, the deprojected distance of the SN is about 30 ± 10 kpc. If we assume that the abundance gradient is similar to the mean value, about −0.02 (dex) kpc^{-1} obtained by Dutil & Roy (1999) for this galaxy type, the expected abundance at the SN location will be ∼8.9 ± 0.2 dex, which is around solar.

Basic information on the four SNe and their host galaxies (taken from LEDA) is reported in Table 1. Two *R*-band images of SN 2006jc at late phases are shown in Fig. 1, and *R*-band images of SNe 2000er and 2002ao in Fig. 2. An image of the host of SN 1999cq can be found in the Lick Observatory Supernova Search web pages.[2] The distances of the four host galaxies were determined using the recession velocities corrected for the effect of the Local Group infall into the Virgo cluster and a value of $H_0 = 71$ km s^{-1} Mpc^{-1}. The adopted distance moduli are reported in Table 1.

The unusual blue colour observed in SN 2006jc and its relatively peripheral location within the host galaxy suggest that this SN suffered very little interstellar extinction. Hereafter we will adopt for SN 2006jc a total reddening of $E(B-V) = 0.02$ (equal to the Galactic component, Schlegel, Finkbeiner & Davis 1998), in agreement with the values adopted by Pastorello et al. (2007a), Foley et al. (2007) and Smith et al. (2008). By contrast, there is indication of some additional extinction inside the parent galaxies for the other three SNe.

The low-resolution spectra of SN 2000er show evidence of narrow interstellar Na I D at the rest wavelength of the host galaxy, indicating that some dust in the parent galaxy is extinguishing the SN light. From the equivalent width of the doublet (EW = 0.48 Å) obtained averaging the measurements from five different spectra, and using the Turatto, Cappellaro & Benetti (2003) relation, we obtain $E(B-V) = 0.08$. Taking into account the Galaxy contribution from Schlegel et al. (1998) we derive a total $E(B-V) = 0.11$. Similarly, for SN 1999cq an upper limit of $E(B-V) \leq 0.45$ was obtained by Matheson et al. (2000) using again the EW of the Na I D interstellar line. However, applying other techniques, they found this limit to be probably not stringent, and a more reliable upper limit was estimated to be $E(B-V) \leq 0.25$, although an even lower, possibly negligible extinction was not excluded. Hereafter we will adopt $E(B-V) = 0.15$ as a best value for SN 1999cq, most of which is due to the host galaxy. Finally, the spectra of SN 2002ao have modest signal-to-noise ratio (S/N) and the detection of narrow interstellar lines is not trivial. We will adopt a total reddening $E(B-V) = 0.25$, as obtained from a comparison with the colours of SN 2006jc at similar phases (Section 3.2, but also fig. 3 in Pastorello et al. 2008).

The values of the total interstellar reddening adopted for the four SNe of our sample are reported in Table 1 along with the epochs of the light-curve maxima, as estimated using spectroscopic and photometric comparison criteria (see Section 3.2 for more details). Hereafter, throughout the paper, the phases computed from the epochs of the maxima will be used.

3 SPECTROSCOPIC OBSERVATIONS

The four SNe discussed in this paper were initially classified as peculiar Type Ib/c SNe (Filippenko 1999; Clocchiatti & Turatto 2000; Dennefeld & Patris 2000; Maury et al. 2000; Filippenko & Chornock 2002; Gal-Yam, Shemmer & Dann 2002a,b; Kinugasa, Kawakita & Yamaoka 2002; Benetti et al. 2006a; Crotts et al. 2006; Fesen, Milisavljevic & Rudie 2006; Modjaz et al. 2006). In this section we present some of these classification spectra plus a few unpublished spectra of SNe 2006jc, 2000er and 2002ao (details are listed in Table 2). These spectra are analysed along with those shown in previous publications (Matheson et al. 2000; Foley et al. 2007; Pastorello et al. 2007a), and the implications are discussed below.

3.1 Early spectra

The only Type Ibn SN for which early phase spectra are available is SN 2000er. Those spectra are shown in Fig. 3 (top panel) and a comparison with later spectra of other SNe Ibn is shown in the bottom panel (Matheson et al. 2000; Foley et al. 2007; Pastorello et al. 2007a).

The spectra of SN 2000er are quite blue, in agreement with its adopted young age at the time of the observations (see Table 2). The first spectrum (November 25) is almost featureless: only the narrow P Cygni lines of He I are clearly visible. The subsequent spectra start to develop more prominent He I emission components, while

[1] http://leda.univ-lyon1.fr/; (Paturel et al. 2003).

[2] http://astro.berkeley.edu/∼bait/1999/sn99cq.html.

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Table 1. Basic information on our SN sample. Distances (d, column 7) and distance moduli (μ, column 8) have been derived from the recession velocities of LEDA corrected for Local Group infall into the Virgo cluster, and assuming $H_0 = 71$ km s^{-1} Mpc^{-1}. In column 6 the integrated metallicity of the host galaxies (see text) is reported. In column 9 the Galactic reddening from Schlegel et al. (1998) and in column 10 the adopted (total) reddening are provided, while in column 11 the Julian Date of the light-curve peak is indicated. The extinction law of Cardelli, Clayton & Mathis (1989), with $R_V = 3.1$, is adopted throughout this paper.

SN	α	δ	Galaxy	Type	12 + log(O/H) (dex)	d (Mpc)	μ (mag)	$E_G(B-V)$ (mag)	$E(B-V)$ (mag)	JD(max) +240 0000	Reference
1999cq	$18^h32^m07\overset{s}{.}10$	$+37°36'44\overset{''}{.}3$	UGC 11268	Sbc	9.3	114	35.29	0.054	0.15	51 348 ± 4	1
2000er	$02^h24^m32\overset{s}{.}54$	$-58°26'18\overset{''}{.}0$	PGC 9132	Sab	9.2	128	35.53	0.033	0.11	51 869 ± 8	2
2002ao	$14^h29^m35\overset{s}{.}74$	$-00°00'55\overset{''}{.}8$	UGC 9299	SABc	8.6	23	31.79	0.043	0.25	52 283 ± 10	2, 3
2006jc	$09^h17^m20\overset{s}{.}78$	$+41°54'32\overset{''}{.}7$	UGC 4904	SBbc	8.5	26	32.04	0.020	0.02	54 008 ± 15	2, 3, 4

(1) Matheson et al. (2000); (2) this paper; (3) Foley et al. (2007); (4) Pastorello et al. (2007a).

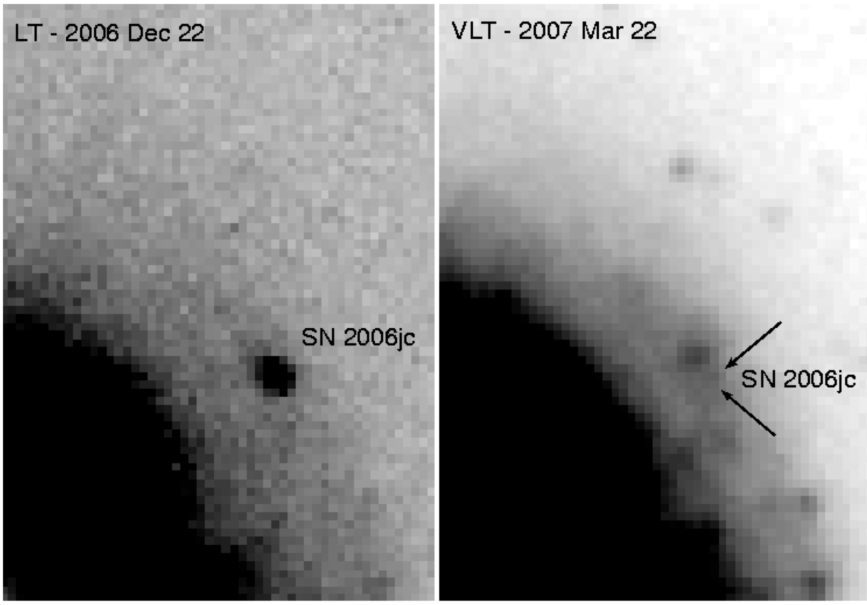

Figure 1. Late R-band images of SN 2006jc. Liverpool Telescope image obtained on 2006 December 22 (left-hand panel) and a very late VLT image (2007 March 22; right-hand panel). In this image, the SN is only marginally detectable and it is very close to a luminous star-forming region. North is down, east is to the left-hand side.

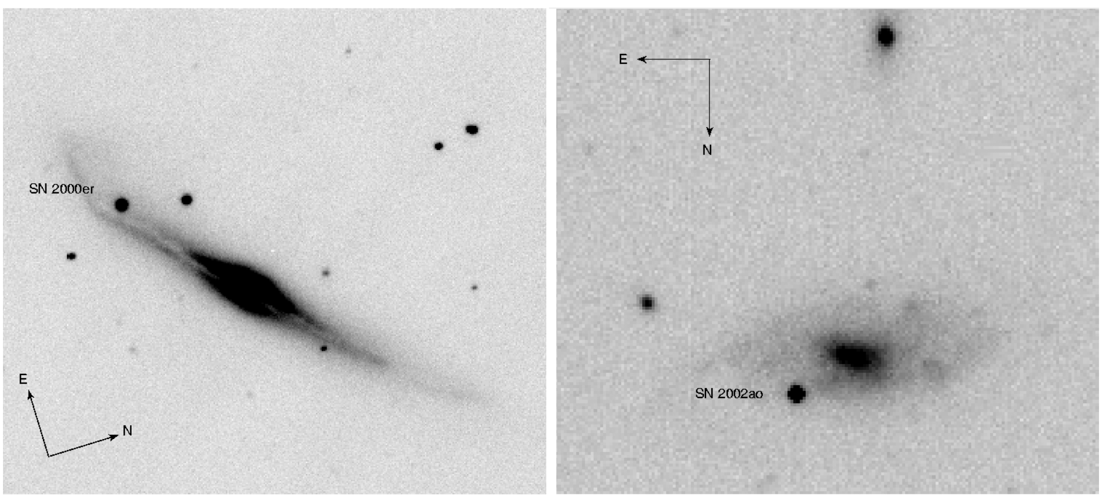

Figure 2. R-band images of SN 2000er (left-hand panel) and SN 2002ao (right-hand panel). They were obtained on 2000 November 26 using the ESO 3.6-m Telescope in La Silla (Chile) and on 2002 February 7 using the IAC 80-cm, in La Palma (Canary Islands, Spain), respectively.

Table 2. Main information on the new spectra of SNe 2006jc, 2000er and 2002ao presented in this paper.

Date	JD	Phase (d)	Instrumental configuration	Range (Å)	Resolution (Å)
			SN 2006jc		
2006 December 20	245 4089.60	81.6	Ekar 1.82 m + AFOSC + gr.4	3650–7800	24
2006 December 26	245 4095.74	87.7	WHT 4.2 m + ISIS + R300B+R158R	3200–9550	7+10
2007 February 08	245 4139.64	131.6	WHT 4.2 m + ISIS + R300B+R158R	3050–9080	7+10
2007 March 22, 23, 24[a]	245 4182.58	174.6	VLT UT1+ FORS2 + gr.300I + OG590	5900–11 100	10
			SN 2000er		
2000 November 25	245 1873.69	4.7	ESO 3.6 m + EFOSC2 + gr.5	5170–9270	16
2000 November 26	245 1874.68	5.7	ESO 3.6 m + EFOSC2 + gr.11	3350–7230	16
2000 November 27	245 1875.72	6.7	ESO 3.6 m + EFOSC2 + gr.13	3670–9290	20
2000 November 29	245 1877.67	8.7	ESO 3.6 m + EFOSC2 + gr.13	3670–9290	20
2000 November 30	245 1878.70	9.7	ESO 3.6 m + EFOSC2 + gr.13	3670–9290	20
			SN 2002ao		
2002 January 30	245 2304.62	21.6	Wise 1 m + FOSC + gm.600	4150–7800	18.5
2002 January 31[b]	245 2306.24	23.2	Gunma 0.65 m + GCS + 300gr./mm	3810–7650	12
2002 February 01	245 2306.61	23.6	Wise 1 m + FOSC + gm.600	4150–7800	18.5
2002 February 05	245 2311.26	28.3	AAT + RGO + gm.300b	3280–9290	6.5
2002 February 08	245 2313.60	30.6	Wise 1 m + FOSC + gm.600	4150–7800	18.5

[a]The final spectrum shown in this paper is obtained averaging six individual VLT spectra with 2820 s of exposure time each, and obtained during three subsequent nights: March 22, 23 and 24. The mean Julian Day (JD) and the phase are computed averaging the JDs of the individual observations. [b]Not shown in Fig. 4 because of its low S/N.

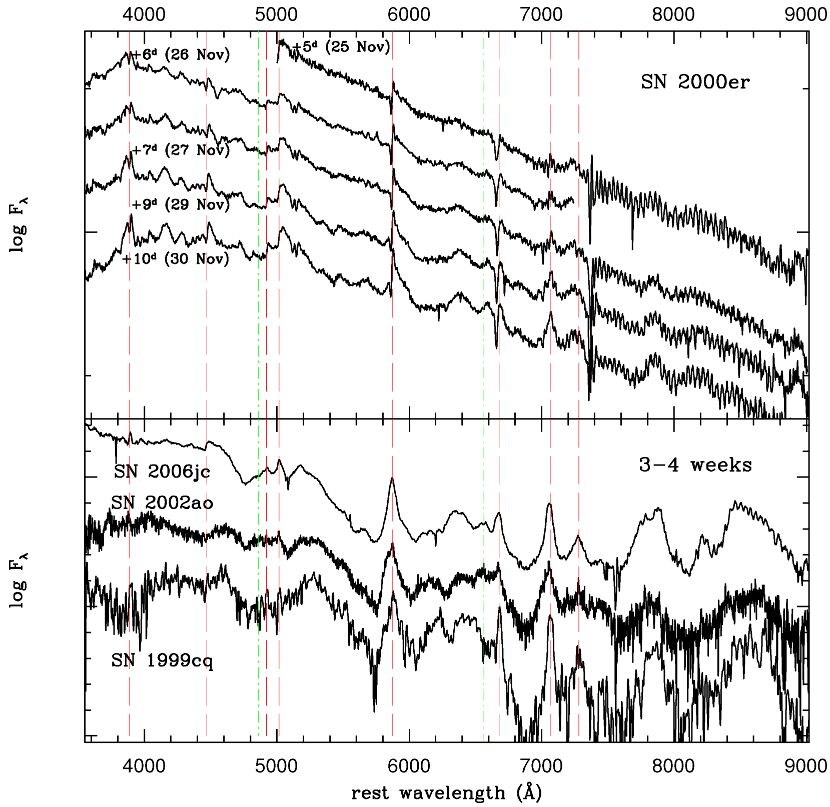

Figure 3. Top: spectroscopic evolution of SN 2000er soon after the explosion. Bottom: comparison with spectra of other SNe Ibn, observed at later phases. Vertical red dashed lines mark the position of the main He I features, while the dot–dashed green lines reveal the rest wavelength position of Hα and Hβ. All spectra have been dereddened as indicated in Table 1. Note the broad O I λ7774 feature beginning to develop in the +7 d spectrum, and becoming stronger at +10 d. The $v_{\rm FWHM}$ of this feature is about 5300 ± 1100 km s^{-1}.

there is no evidence for the H Balmer lines. The prominent He I lines show narrow P Cygni profiles. This is a significant difference compared to the spectra of other SN Ibn events presented so far (Matheson et al. 2000; Foley et al. 2007; Pastorello et al. 2007a). These narrow components are indicative of the presence of a slowly expanding (∼800–900 km s^{-1}) CSM around the SN. The same He I lines show however also broader wings, with full width at half-maximum (FWHM) velocity $v_{\rm FWHM}$ ∼ 5000 km s^{-1}, suggesting that some helium is also present in the fast-moving SN ejecta. A broad O I λ7774 feature is detected with a $v_{\rm FWHM}$ consistent with that of the broad He I line wings. The broad Ca II infrared (IR) feature has not yet developed. Although the spectra of SN 2000er are from an early phase, they show most of the features detected in the spectra of other SNe Ibn (Fig. 3).

We note that SN 1999cq was discovered very young (Matheson et al. 2000), and of all the SNe Ibn it is very likely that this is the one discovered closest to the explosion epoch. However, the first spectrum by Matheson et al. (2000) was not taken until a few weeks after the discovery announcement, hence an opportunity for very early spectral coverage was missed for this object.

3.2 Intermediate-age spectra and phase calibration

Using the spectra available for the four SNe, along with the photometric data (see Section 4), we have attempted a consistent estimate of the phase of all the objects of our Type Ibn SN sample. The almost featureless spectra of SN 2000er and their rapid evolution (Fig. 3) are indicative that the SN was probably discovered within about one week from the explosion. Similarly, the photometric data of SN 1999cq, and in particular the stringent pre-discovery limit, suggest that this object was also discovered very young (see Matheson et al. 2000, and Section 4). By contrast, the presence of more prominent spectral features in the SN 2006jc spectra indicates that this object was discovered at a slightly later phase, a couple of weeks after the explosion or ∼10 d after maximum light. As a further consistency check on the phase calibration, we have verified that the SN 1999cq spectrum presented in Matheson et al. (2000) closely resembles the spectrum of SN 2006jc obtained on 2006 October 24.

Dating SN 2002ao is less straightforward because this object was discovered late and it was not intensively monitored. Some spectra of SN 2002ao, obtained when the SN was already quite evolved compared to SN 2000er, are shown in Fig. 4. A unique and remarkable feature of the spectrum at +6 weeks is that the He I lines show a double-component profile, with a narrow component (900–1500 km s^{-1}) on top of a broader one (4000–5000 km s^{-1}). This broader component was indeed not evident in the spectra of SN 2006jc (see e.g. the unblended He I 7065 Å feature in Fig. 4, bottom panel). This indicates that, although most He was lost by the progenitor of SN 2002ao during the WR phase, some He was still present in the star's envelope and ejected at the time of the SN explosion (analogous to that observed in SN 2000er). Apart from this difference, the spectra of SN 2002ao are rather similar to those of SN 2006jc obtained 1–2 months post-maximum. The phase of these spectra was therefore calibrated with reference to SN 2006jc, using as a reference a best-fitting comparison code (Passpartoo, Harutyunyan et al. 2008). We gave more weight to the bluest (below ∼5500 Å) and the reddest (beyond about 7200 Å) regions of the spectrum than to the intermediate wavelength region (5500–7200 Å) as these were less contaminated by the prominent narrow circumstellar lines. In particular, we note that the highest S/N spectra of SN 2002ao obtained on February 5 and February 21 (Foley et al. 2007, see also Fig. 4) provide a good fit (in terms of line velocity and relative strengths of the broad lines) to the spectra of SN 2006jc at phases +24 and +41 d, respectively (Pastorello et al. 2007a).

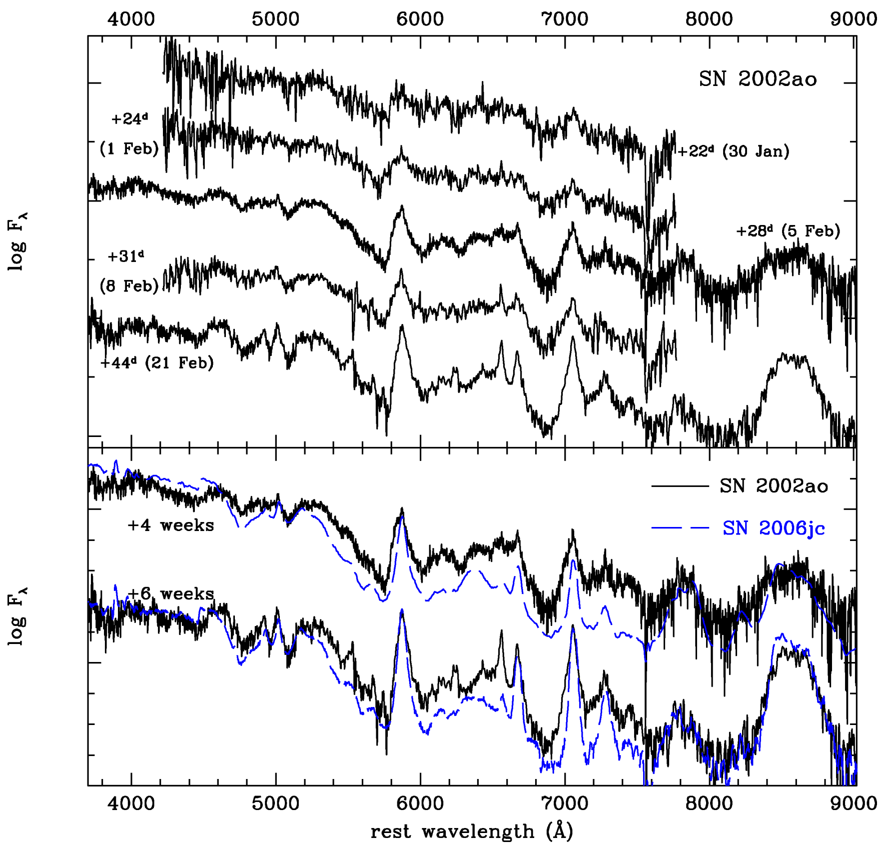

Figure 4. Top: spectroscopic evolution of SN 2002ao. The February 21 spectrum from Foley et al. (2007) has been included. Bottom: comparison of spectra of SN 2002ao and SN 2006jc (Foley et al. 2007; Pastorello et al. 2007a) at about 4 weeks and 6 weeks post-maximum. The spectra of SN 2002ao have been dereddened by $E(B-V) = 0.25$ mag, while those of SN 2006jc by $E(B-V) = 0.02$ mag.

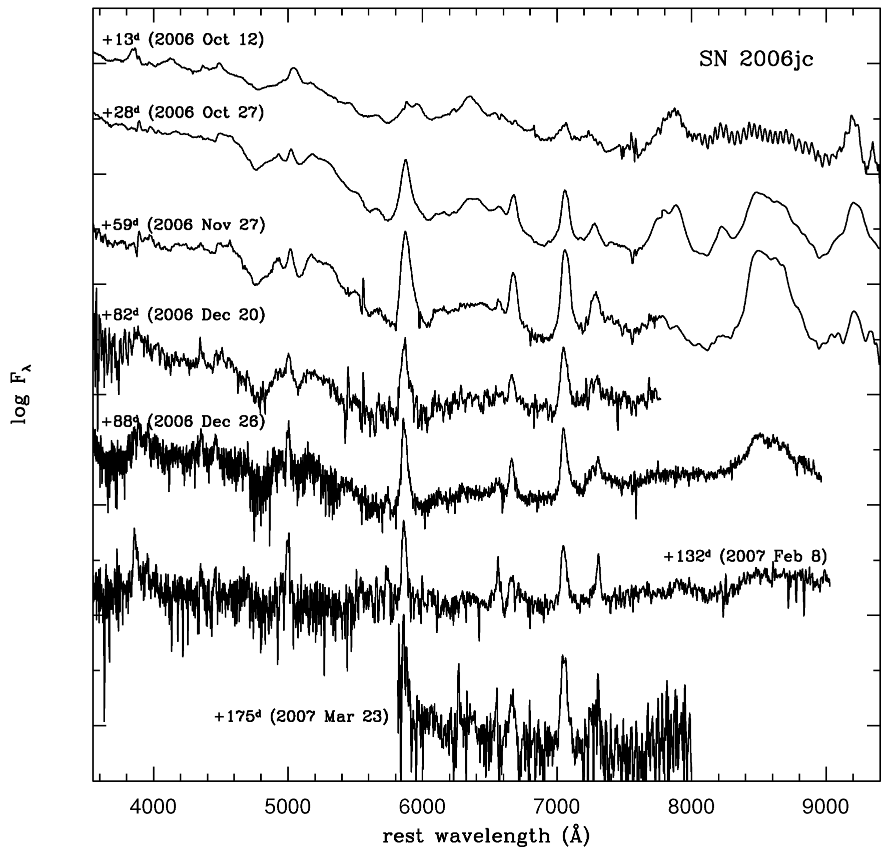

Figure 5. Spectroscopic evolution of SN 2006jc. Some early-time spectra from Pastorello et al. (2007a) plus unpublished late-time spectra are shown.

3.3 Nebular spectra

Contrary to other Type Ibn SNe for which only few sparse observations exist, SN 2006jc was extensively monitored during the first ~70 d after discovery (Foley et al. 2007; Pastorello et al. 2007a). This makes SN 2006jc the best observed object of this class. The existing spectral data base of SN 2006jc covers its evolution starting from about 10 d after the inferred maximum light (see Table 1 and Section 3.2). Some early spectra from Pastorello et al. (2007a) and new late-time spectra of SN 2006jc are shown in Fig. 5. The VLT spectrum was obtained by merging a sequence of spectra obtained between 2007 March 22 and 24 (with an integrated exposure time of more than 6 h). This is, to our knowledge, the latest optical spectrum existing for an object of this class.

The last two spectra (2007 February and March) are completely different from those obtained in 2006 December (see Fig. 5). They do not show the strong blue continuum characterizing the spectra of SN 2006jc at earlier phases or the flux excess at the redder wavelengths discussed by Smith et al. (2008). Moreover there is no clear evidence of the broad emission lines characterizing SNe Ib/c at similar phases. Instead, prominent and narrow ($v_{\rm FWHM} \approx$ 1800–1900 km s^{-1}) He I lines can be identified and still dominate the spectrum about 6 months after the explosion. A further difference to earlier spectra of SN 2006jc lies in the strength of Hα, which is almost comparable with the 6678 Å He I line in the February spectrum (phase ~ +132 d; see Fig. 5), although even narrower ($v_{\rm FWHM} \sim$ 1000 km s^{-1}). This indicates the presence of an outer, H-rich circumstellar shell beyond the He I layer which is likely ionized by photons from ejecta–CSM interaction or by high-energy photons propagated through the He-rich region.

3.4 Overall evolution

The spectra collected for our SN Ibn sample allow us to illustrate the spectroscopic evolution for this SN type (see Fig. 6). The phases are calibrated with reference to the epochs of maximum reported in Table 1.

Despite a considerable uncertainty in the explosion epochs and in the interstellar reddening estimates, there appears to be a remarkable homogeneity in the spectroscopic properties among the objects. This is also evident from a check of the profiles of the narrow He I lines in our SN sample. The evolution of the line profiles of the features at 5876, 6678 and 7065 Å is shown in Fig. 7 and has been obtained making use of the spectra of four different SNe Ibn. This homogeneity in the spectral properties would be quite surprising if the ejecta were strongly interacting with a pre-existing CSM, because the density, geometry and composition of the CSM would be expected to affect significantly the evolution of SNe Ibn. One possibility is that the homogeneity in the observed properties of SNe Ibn may indicate that the ejecta–CSM interaction is playing a minor role in the evolution of these SNe.

The most significant difference among SNe Ibn lies in the strength of the narrow H spectral lines (Fig. 6, where the position of Hα is marked by a dot–dashed vertical line, see also Fig. 7, central panel). This likely indicates some variation in the abundance of H in the

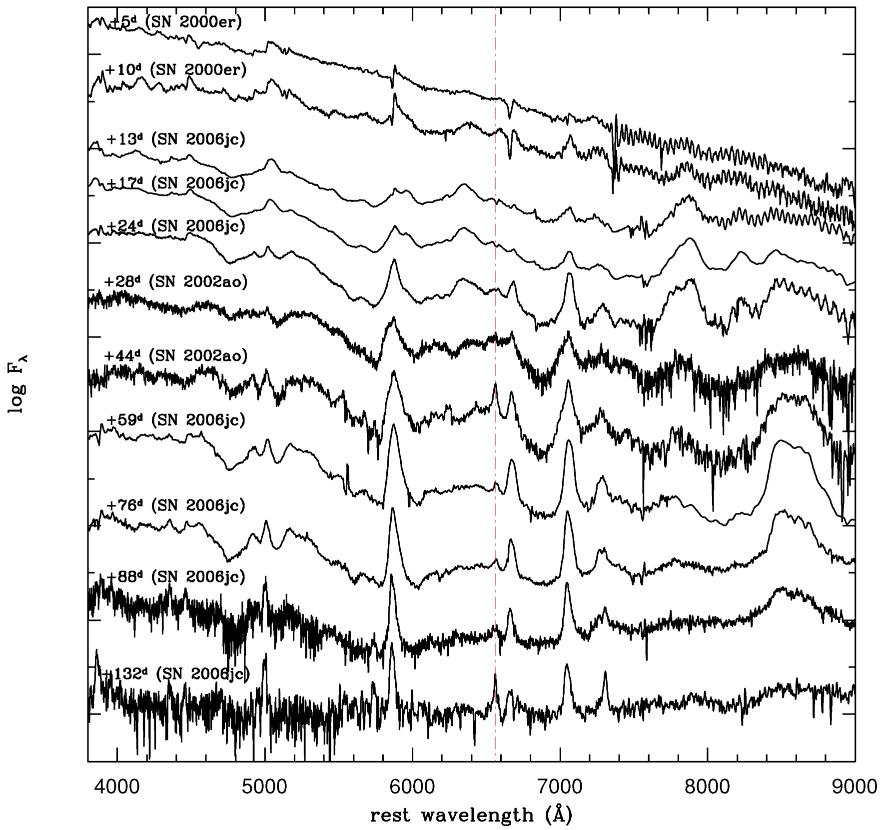

Figure 6. Spectroscopic evolution for a representative sample of SNe Ibn. The spectra are reddening-corrected. The +44 d spectrum of SN 2002ao is from Foley et al. (2007); those of SN 2006jc from +13 to +76 d are from Pastorello et al. (2007a). The vertical dot–dashed line marks the Hα rest wavelength.

innermost CSM region. To a lesser degree there are differences in the widths and profiles of the circumstellar He I lines.

4 LIGHT CURVES

New photometric data of SNe 2000er, 2002ao and 2006jc are reported in Table 3. The photometric measurements in the reduced images (i.e. after overscan, bias and flat-field corrections) have been performed using standard point spread function (PSF) fitting procedures in the cases of SNe 2000er and 2006jc, since reliable galaxy templates were not available. Conversely, for SN 2002ao we have subtracted the host galaxy contribution using images of the SN field obtained in 2007 April, using the 1.82-m Copernico Telescope of Mt Ekar (Asiago, Italy). Photometric zero-points were then computed using standard fields from the Landolt (1990) catalogue observed during some photometric nights, and then the SN magnitudes were calibrated after comparison with the magnitudes of reference stars in the fields of the three SNe (for more details on the method see e.g. Pastorello et al. 2006). The local sequence calibrated for SN 2006jc is the same as adopted in Pastorello et al. (2007a).

SN 2000er was also observed in J, H and K bands with the SOFI near-IR (NIR) imager mounted on ESO NTT at a single epoch, on 2001 January 11. The SOFI images were reduced using standard IRAF procedures and the photometry was performed using PSF fitting procedures. The photometric data were calibrated using 2MASS magnitudes. This yielded magnitudes of 20.20 ± 0.26, 20.37 ± 0.30 and 19.45 ± 0.28 for SN 2000er in the J, H and K bands, respectively. Apart from SN 2006jc, SN 2000er is the only Type Ibn SN which was observed in the NIR domain.

In Fig. 8 the R-band absolute light curve of SN 2000er is compared with the light curves of SNe 2006jc (Foley et al. 2007; Pastorello et al. 2007a), 1999cq (unfiltered, approximately R band, Matheson et al. 2000) and 2002ao (Foley et al. 2007). These light curves were computed by adopting the distances and interstellar extinction values reported in Table 1. Since the host galaxy of SN 2000er has relatively high redshift, a K-correction to the observed magnitudes was applied. The correction (always within 0.1 mag) was computed making use of the early-time SN spectra plus a late-time spectrum of SN 2006jc, artificially extinguished and redshifted to match the values of $E(B-V)$ and redshift of the host galaxy of SN 2000er. Although also the host galaxy of SN 1999cq has a high redshift, no K-correction was applied to the data of Matheson et al. (2000) because of the lack of spectral coverage. Actually, the redshift effect on the broad-band magnitudes of SN 1999cq might be non-negligible.

SNe 1999cq and 2000er are particularly important because they show the early post-maximum evolution of the light curve for representative objects of this family. The evolution during the first month after peak is remarkably homogeneous. A very bright peak magnitude (not far from $M_R \sim -20$) is probably a common characteristic of SNe Ibn. At about 40 d, the light curve of SN 2006jc settles on a slower decline, indicating that the SN has likely reached the exponential tail. Soon after (between 50 and 60 d), the light curve becomes again steeper, with the slope being similar to those of other SNe Ibn observed at late phases. The very rapid luminosity

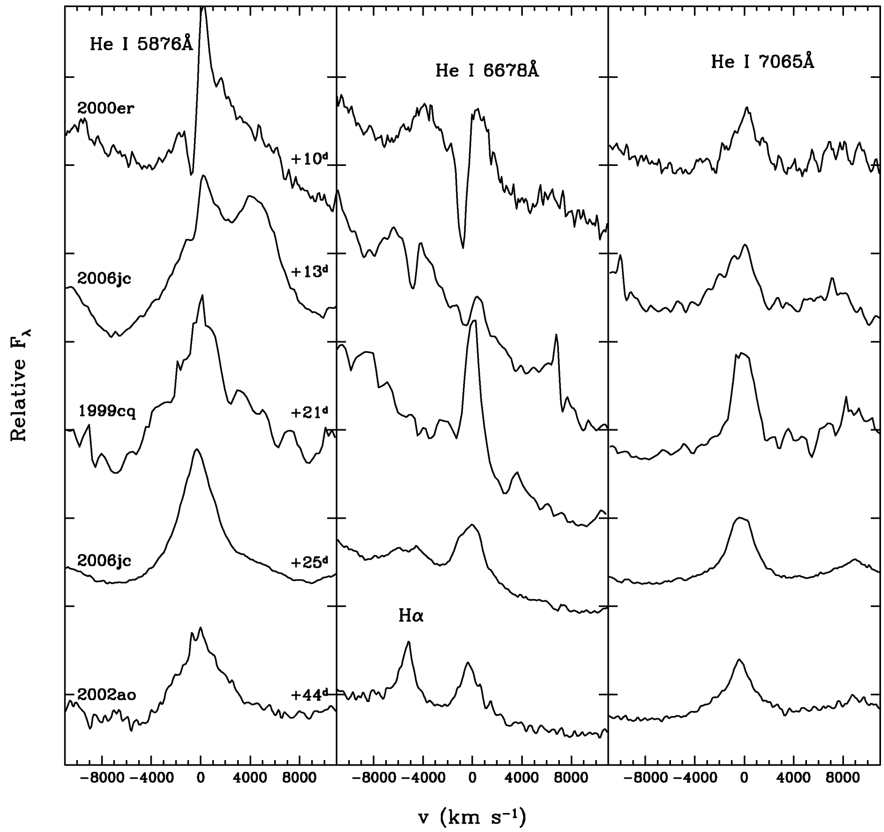

Figure 7. Profiles of some selected He I lines for a representative sample of spectra of SNe Ibn. The spectra are reddening-corrected. The +21 d spectrum of SN 1999cq is from Matheson et al. (2000), that of SN 2002ao at +44 d is from Foley et al. (2007), while those of SN 2006jc from +13 to +25 d are from Pastorello et al. (2007a).

decline may indicate that either a very small amount of ^{56}Ni is ejected by the objects of this class, or that new dust formed in the SN ejecta or in the surrounding CSM. The formation of new dust is supported by the large IR excess observed in SN 2006jc starting from 1 month after the discovery (Arkharov et al. 2006; Di Carlo et al. 2007; Sakon et al. 2007; Mattila et al. 2008; Smith et al. 2008; Tominaga et al. 2007), a progressively redder spectral continuum and a clear red-wing attenuation in the profiles of the He I circumstellar spectral lines (Mattila et al. 2008; Smith et al. 2008). Condensation of dust in the ejecta of a few core-collapse SNe has been observed at late times (see Meikle et al. 2007, and references therein). Moreover, another scenario in which new dust condensed in a cool dense shell produced by the impact of the SN ejecta with a dense CSM has previously been proposed to explain the IR excess observed in the Type IIn SN 1998S at epochs later than 300 d (Pozzo et al. 2004). In SN 2006jc it is likely that a similar mechanism took place but producing new dust at a much earlier epoch (see Mattila et al. 2008; Smith et al. 2008, and Section 4.1 of this paper).

Unfortunately, so far no SN Ibn has been observed during the rising phase to maximum. However, some detection limits were obtained close enough to the first detection and indicate that the rising branch of the light curve is extremely fast, similar to what we see in some core-collapse SNe which show evidence of interaction with a CSM (e.g. SNe 1983K, 1993ad and 1994W, Niemela, Ruiz & Phillips 1985; Phillips et al. 1990; Pollas, Cappellaro & della Valle 1993; Tsvetkov & Pavlyuk 1995; Sollerman, Cumming & Lundqvist 1998; Chugai et al. 2004), but also in more classical non-interacting Type II SNe (e.g. SNe 2005cs and 2006bp; Quimby et al. 2007; Pastorello et al., in preparation).

4.1 Quasi-bolometric light curve

In Fig. 9 the quasi-bolometric (*uvoir*) light curve of the representative Type Ibn SN 2006jc (filled circles), is compared with the curves of some well-observed Type Ib/c SNe and the Type IIn SN 1999E (though the core-collapse nature of this SN is disputed due to the similarity to SN 2002ic, see e.g. Hamuy et al. 2003; Benetti et al. 2006b). All light curves are computed by integrating the fluxes in the optical (*UBVRI*) and NIR (*JHK*) bands. The *uvoir* curve of SN 1999E is remarkably flatter and more luminous than that of any other SN in Fig. 9. This is because it is mostly powered by the energy output from the interaction between SN ejecta and CSM (Rigon et al. 2003). The *uvoir* curve of SN 2006jc is similar to those of non-interacting, rather luminous core-collapse SNe (Fig. 9), suggesting that the ejecta–CSM interaction probably plays only a minor role in the luminosity evolution of this SN Ibn (Section 4.2, see also Tominaga et al. 2007).

The fast rise, asymmetric, luminous peak and rapid decline of the unfiltered light curve of SN 1999cq (see Fig. 8) are reminiscent of some bright SNe IIL (e.g. SNe 1979C and 1980K, see Patat et al. 1994, and references therein). Bartunov & Blinnikov (1992) explained the observed properties of the early light curves of luminous Type IIL SNe with a standard core-collapse explosion in which the optical peak results from the reprocessing of ultraviolet (UV) photons in a circumstellar shell generated by a

Table 3. Additional, unpublished late-time photometry of SN 2006jc, plus new photometry for SNe 2000er and 2002ao.

Date	JD	Phase	U	B	V	R	I	Instrument
SN 2006jc								
2006 December 20	245 4089.65	81.7		19.53 (0.09)	19.53 (0.07)	19.16 (0.08)	18.16 (0.06)	Mt.Ekar 1.82 m + AFOSC
2006 December 22	245 4091.57	83.6	18.95 (0.05)	20.03 (0.06)	19.98 (0.06)	19.69 (0.06)	18.44 (0.03)	LT 2.0 m + RatCam
2006 December 30	245 4099.51	91.5	19.67 (0.32)		20.74 (0.21)	20.27 (0.17)	19.05 (0.07)	LT 2.0 m + RatCam
2007 January 08	245 4109.51	101.5	>20.21	21.62 (0.22)	21.64 (0.34)	21.15 (0.22)	19.90 (0.12)	LT 2.0 m + RatCam
2007 January 14	245 4114.70	106.7		22.11 (0.22)	22.04 (0.38)	21.60 (0.28)	20.12 (0.25)	LT 2.0 m + RatCam
2007 January 17	245 4117.70	109.7		22.57 (0.13)	22.59 (0.26)	21.85 (0.18)	20.30 (0.10)	LT 2.0 m + RatCam
2007 February 06	245 4138.44	130.4		>22.71	>22.70	22.93 (0.38)	21.17 (0.41)	LT 2.0 m + RatCam
2007 February 07	245 4139.45	131.5				23.05 (0.21)	21.33 (0.14)	WHT 4.2 m + Aux Port Imager
2007 February 08	245 4139.78	131.8			23.59 (0.38)			WHT 4.2 m + Aux Port Imager
2007 February 11	245 4143.38	135.4		>23.29	>23.10	23.46 (0.41)	21.64 (0.28)	LT 2.0 m + RatCam
2007 March 11	245 4171.41	163.4			24.27 (0.14)	24.05 (0.25)	22.96 (0.10)	WHT 4.2 m + Aux Port Imager
2007 March 22	245 4181.57	173.6				24.37 (0.45)	23.30 (0.68)	VLT-UT2 + FORS1
SN 2000er[a]								
2000 November 25	245 1873.68	4.7				16.29 (0.01)		ESO 3.6 m + EFOSC2
2000 November 25	245 1873.69	4.7				16.31 (0.01)		ESO 3.6 m + EFOSC2
2000 November 26	245 1874.67	5.7		16.73 (0.01)	16.47 (0.01)	16.36 (0.01)		ESO 3.6 m + EFOSC2
2000 November 27	245 1875.70	6.7				16.54 (0.01)		ESO 3.6 m + EFOSC2
2000 November 29	245 1877.65	8.7				16.65 (0.01)		ESO 3.6 m + EFOSC2
2000 November 29	245 1877.66	8.7				16.65 (0.01)		ESO 3.6 m + EFOSC2
2000 November 30	245 1878.68	9.7				16.74 (0.01)		ESO 3.6 m + EFOSC2
2001 February 02	245 1942.54	73.5		23.42 (0.10)	23.38 (0.20)	23.32 (0.17)		ESO 3.6 m + EFOSC2
SN 2002ao								
2002 February 07	245 2312.74	29.7		16.79 (0.03)	16.51 (0.02)	16.21 (0.02)	16.09 (0.02)	IAC 0.80 m + CCD
2002 February 08	245 2313.75	30.8		16.88 (0.06)	16.60 (0.02)	16.29 (0.02)	16.21 (0.03)	IAC 0.80 m + CCD
2002 February 10	245 2315.66	32.7		17.09 (0.05)	16.80 (0.04)		16.37 (0.03)	IAC 0.80 m + CCD
2002 February 13	245 2319.33	36.3				16.91 (0.05)		Kiso 1.05 m + CCD
2002 February 13	245 2319.34	36.3				16.93 (0.04)		Kiso 1.05 m + CCD
2002 February 14	245 2320.34	37.3		17.75 (0.24)	17.34 (0.25)	17.25 (0.26)	16.97 (0.14)	Kiso 1.05 m + CCD
2002 February 18	245 2324.62	41.6		18.09 (0.04)		17.42 (0.03)		Wise 1.0 m + CCD
2002 March 04	245 2338.57	55.6			18.82 (0.41)	18.88 (0.55)	18.37 (0.30)	Wise 1.0 m + CCD
2002 March 05	245 2339.52	56.5			18.98 (0.31)	19.04 (0.28)	18.43 (0.23)	Wise 1.0 m + CCD
2002 March 07	245 2341.57	58.6			19.53 (0.21)	19.17 (0.27)	18.88 (0.21)	Wise 1.0 m + CCD
2002 April 02	245 2366.95	84.0			22.15 (0.41)	22.03 (0.44)		Kuiper 1.55 m + CCD
2002 April 03	245 2367.94	84.9			22.21 (0.44)			Kuiper 1.55 m +CCD
2002 April 05	245 2369.50	86.5			>20.78	>20.61	>20.27	Wise 1.0 m + CCD
2002 April 13	245 2377.51	94.5		>20.10	>20.64	>19.77	>19.67	Wise 1.0 m + CCD
2002 April 13	245 2378.42	95.4			>18.49	>18.91		Wise 1.0 m + CCD
2002 April 18	245 2383.41	100.4			>20.61	>20.25	>19.83	Wise 1.0 m + CCD
2002 May 05	245 2399.84	116.8		>22.14	>22.06	>22.19	>22.00	Bok 2.3 m + CCD
2007 April 16	245 4206.50	1923.5		>22.69	>22.32	>22.08	>22.04	Mt Ekar 1.82 m + AFOSC
2007 April 19	245 4210.49	1927.5		>21.87	>22.13	>21.86	>21.15	Mt Ekar 1.82 m + AFOSC

[a] *K*-corrected magnitudes of SN 2000er. The *K*-correction applied to the data of 2001 February 2 was estimated using a spectrum of SN 2006jc at similar phase (+74 d), reddened by $E(B-V) = 0.11$ and then shifted to the z value of the galaxy hosting SN 2000er.

superwind of the SN precursor. Alternatively, the early light curve of SNe Ibn might be equally well explained invoking a mechanism analogous (though on a shorter time-scale) to the H recombination which produces the long-duration phase with almost constant luminosity (plateau) characterizing SNe IIP. In the case of SNe Ibn, the recombination of the residual He envelope could be responsible for the asymmetric, luminous light-curve peak (see Section 4.2).

In Fig. 9 we also show the light curve of SN 2006jc obtained by integrating the flux contribution from the optical bands only (open circles). Starting from 50–60 d post-maximum, this diverges significantly from the *uvoir* light curve (including the NIR contribution, filled circles), suggesting that a significant amount of dust is forming, extinguishing the light at the optical wavelengths and re-emitting it in the IR domain (for details, see Mattila et al. 2008). Since similar steep decays in the optical light curves are also observed in SNe 1999cq and 2002ao (see also Foley et al. 2007), we could reasonably argue that the formation of a significant amount of dust might be a common characteristic of most Type Ibn events. Unfortunately, apart from SN 2006jc and only one epoch of NIR observations of SN 2000er with rather large photometric uncertainties, no other IR observations are available for other SNe Ibn to test for the appearance of an IR excess contemporaneous with the rapid optical luminosity decline. This phenomenon is observed at quite early stages in SN 2006jc and, as already indicated, is probably due to dust forming in a rapidly cooling shell as a result of the ejecta–CSM shock interaction. This scenario is discussed extensively in Mattila et al. (2008) and Smith et al. (2008).

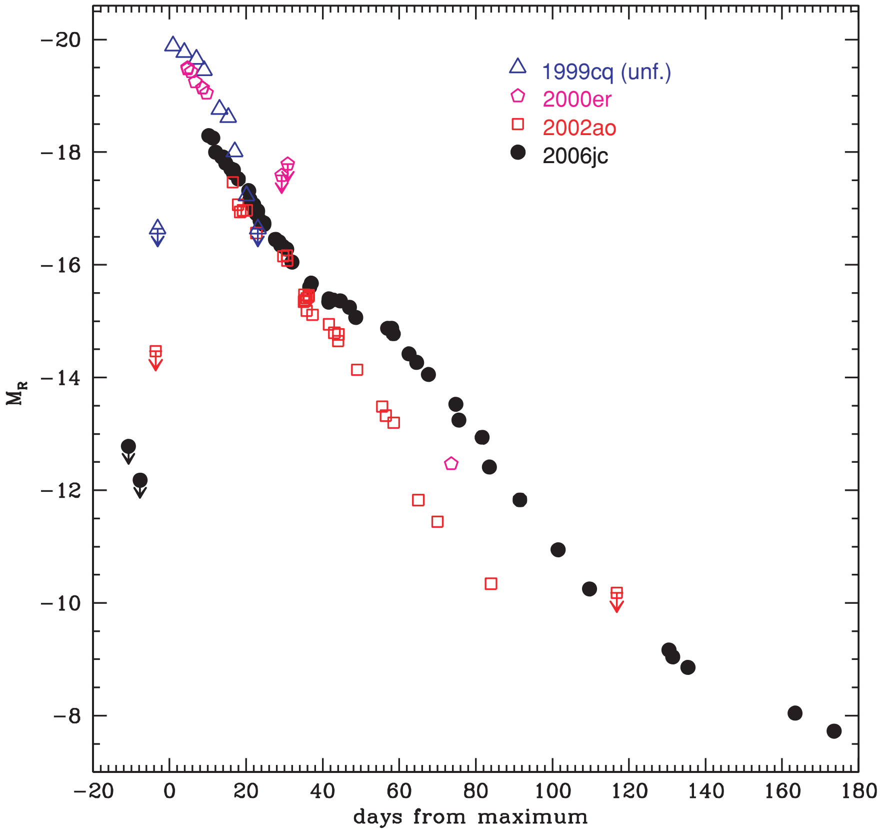

Figure 8. *R*-band absolute light curves for our 2006jc-like SN sample, obtained with the distance and reddening assumptions of Table 1. The unfiltered observations of SN 1999cq from Matheson et al. (2000) are also shown. The most significant detection limits are also reported.

4.2 Light-curve modelling

One way to derive information on the explosion parameters of SNe is the modelling of the bolometric light curve. Hereafter, we will assume that the interaction between ejecta and CSM plays a minor role in the bolometric evolution of SNe Ibn. This is somewhat discrepant with some observed spectral features and with the X-ray detection of at least one of them, SN 2006jc (Brown, Immler & Modjaz 2006; Immler, Modjaz & Brown 2006; Immler et al. 2008), both of which would suggest that some interaction is actually occurring. However, the X-ray luminosity (Immler et al. 2008) is rather low compared to the IR luminosity at the same epochs, and this would be against a strong interaction scenario. Then, SNe Ibn show fast-evolving quasi-bolometric light curves (see Fig. 9), homogeneous spectrophotometric evolution and SN 2006jc was undetected at radio wavelengths soon after its discovery. The radio luminosity of SN 2006jc was indeed at least 100 times less than that of the broad-line SN Ic 1998bw (Soderberg 2006), and at most comparable with those of normal, non-interacting Type Ib/c SNe (Berger et al. 2003). All of these seem inconsistent with a scenario in which the SN ejecta are strongly interacting with the CSM, at least during the first few months.

We consider the case of the well-observed SN 2006jc as representative for the entire class. Here we make use of blackbody luminosities from Mattila et al. (2008) obtained by fitting two components (hot photosphere and warm dust) to the optical to NIR spectral energy distribution (SED) of the SN to construct another bolometric light curve for SN 2006jc. At early times a significant contribution to the total luminosity is expected to come from wavelengths shorter than ∼3500 Å, while at later epochs most of the contribution is in the IR domain. Since there were no NIR data for 2006jc earlier than ∼55 d, the blackbody luminosities were obtained only for epochs later than this (Mattila et al. 2008). However, at +55 d the blackbody bolometric luminosity was dominated (more than 90 per cent of the total luminosity) by the hot component and was about two times higher (mainly due to the UV contribution) than the *uvoir* luminosity calculated in Section 4.1 of this paper. Missing any information on the blackbody bolometric luminosity at earlier epochs, we scale up the luminosity earlier than +55 d (see Section 4.1) by a factor of 2. For epochs later than +55 d we scale the *uvoir* light curve up to match the appropriate blackbody luminosities. This provides a rough estimate (probably a lower limit) to the early-time bolometric luminosity of SN 2006jc. The resulting bolometric light curve is shown in Fig. 10, where it is compared with the models described below.

In our attempt to reproduce its peculiar evolution, we model the bolometric light curve of SN 2006jc using three different explosion scenarios. In one of the models (model C) we also take into account a significant contribution to the energy output from the recombination of a residual He envelope: this may be partly responsible for the asymmetric peak and the steep post-maximum luminosity decay. The He recombination is an additional ingredient to a more traditional, simplified treatment of the bolometric light curves of SNe Ib/c (Arnett 1982), in which the SN evolution can be schematically divided into the photospheric (diffusive) phase and the nebular (radioactive) phase. The ejecta are assumed to be in homologous expansion and spherically symmetric. During the photospheric phase, we also assume that the energy output

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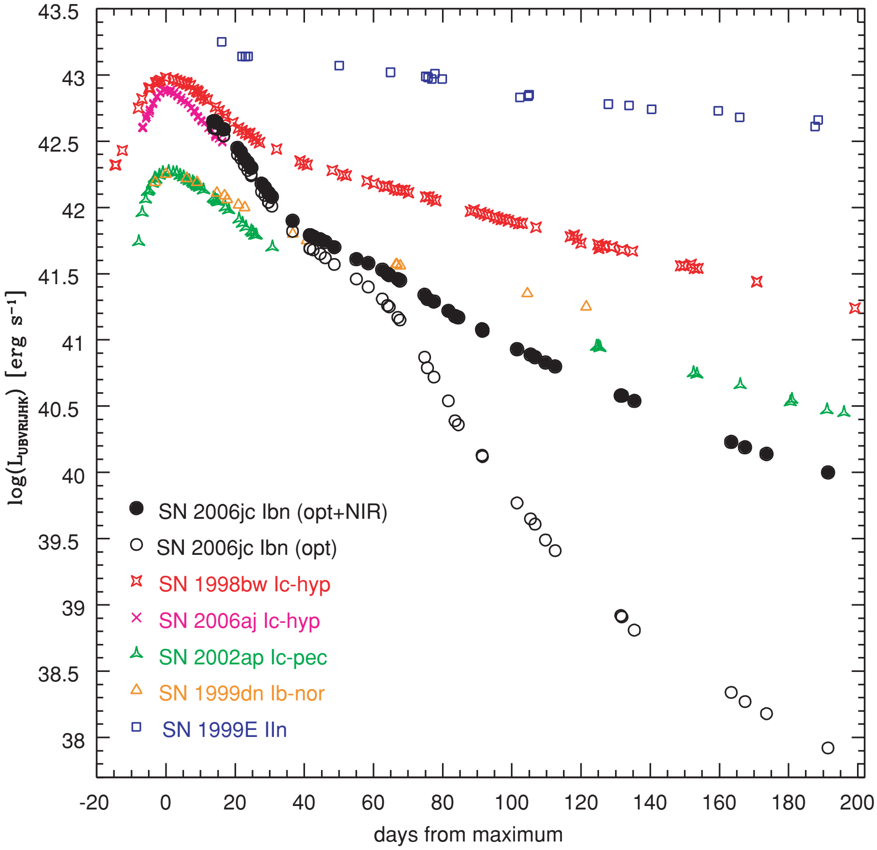

Figure 9. Quasi-bolometric (optical + NIR) light curves of luminous core-collapse SNe: the SN Ibn 2006jc (filled circles), the hypernovae SN 1998bw (Galama et al. 1998; McKenzie & Schaefer 1999; Sollerman et al. 2000; Patat et al. 2001) and SN 2006aj (Campana et al. 2006; Cobb et al. 2006; Mirabal et al. 2006; Pian et al. 2006; Sollerman et al. 2006); the broad-lined but normally luminous Type Ic SN 2002ap (Foley et al. 2003; Yoshii et al. 2003; Tomita et al. 2006); the Type Ib SN 1999dn (Benetti et al., in preparation) and the Type IIn SN 1999E (Rigon et al. 2003, though the core-collapse nature of this SN 2002ic-like event is debated). The light curve of SN 2006jc obtained integrating the optical bands only is also reported (empty circles), showing the dramatic decline of the optical luminosity at ~2 months post-maximum. The comparison between the integrated optical and optical plus NIR light curves visualizes that after 50–60 d most of the SN flux is emitted in the NIR region (Mattila et al. 2008). The NIR data used to compute the quasi-bolometric light curve of SN 2006jc are from Arkharov et al. (2006), Kawabata et al. (2007) and Mattila et al. (2008).

comes from the internal thermal energy of the ejecta, the recombination of the residual He envelope and the energy produced by the ^{56}Ni $\rightarrow$ ^{56}Co $\rightarrow$ ^{56}Fe decay chain. During the nebular phase, the ejecta are optically thin and the SN luminosity is merely supported by the energy deposition of γ-rays from the ^{56}Co decay. In the models, the effects of incomplete γ-ray trapping are taken into account. More details on the bolometric light-curve modelling adapted to H-deprived core-collapse SNe can be found in Arnett (1982), while the treatment of He recombination is suitably adapted from the analysis presented in Zampieri et al. (2003) for Type II SNe with massive H envelopes.

Satisfactory fits to the post-peak bolometric light curve of SN 2006jc are obtained assuming JD$_{exp}$ = 245 4000 as an indicative explosion epoch. After 4 months, the bolometric light curve of SN 2006jc flattens, possibly because of the increasing contribution from the ejecta–CSM interaction or contamination from the galaxy background, and deviates significantly from the models (Fig. 10). Model A (dot–dashed green line in Fig. 10), which has the biggest initial radius ($\sim 2 \times 10^{13}$ cm), the lowest expansion velocity (v_0 = 8000 km s^{-1}) and a very low ejecta mass, fits quite well the observed SN data at early times. In this case a low explosion energy ($<10^{51}$ erg) and 0.2– 0.3 M$_\odot$ of radioactive ^{56}Ni are required. Such amount of ^{56}Ni, which is surprisingly large compared with the small total ejected mass, is necessary to reproduce the SN light curve. However, if the late-time light curve is contaminated by ejecta–CSM interaction, the ejected ^{56}Ni mass might be significantly lower. Model B (blue dashed line) has a smaller initial radius ($R_0 = 4 \times 10^{12}$ cm), moderate ejected mass (about 1 M$_\odot$), large ^{56}Ni mass (~0.4 M$_\odot$) and a rather standard explosion energy (3×10^{51} erg). Finally, model C (red dotted line) is the one with the smallest initial radius (around 10^{12} cm) and the highest ejected mass (~5 M$_\odot$). It requires a very high explosion energy (about 10^{52} erg) and 0.25 M$_\odot$ of ^{56}Ni. In this model, the recombination of the He envelope appears to significantly affect the early-time light curve, producing a peak at about 25 d after the explosion. Model A fits the early-time bolometric curve of SN 2006jc very well, although the initial radius is unreasonably large for a WR star, which is expected to be much more compact. Despite the three best-fitting models appear to be somehow degenerate in the post-peak phase, the late-time bolometric curve of SN 2006jc seems better matched by model C. The parameters adopted for the three models are listed in Table 4.

The set of models allows us to constrain the radioactive ^{56}Ni mass to be in the range 0.2– 0.4 M$_\odot$. However, a significant contribution to the luminosity from the ejecta–CSM interaction would imply a much lower ^{56}Ni mass. The total ejected mass (and hence the progenitor mass) cannot be well constrained, since the three models

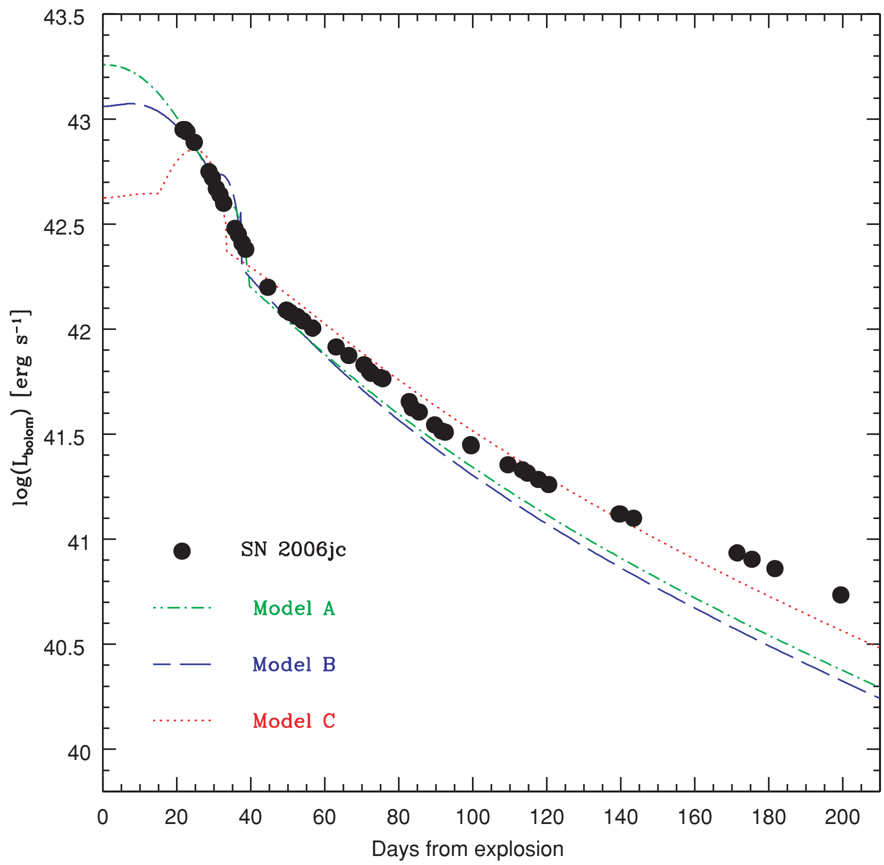

Figure 10. Comparison between the bolometric light curve of SN 2006jc (filled black points) and the models A (large initial radius, small mass, low energy; green dot–dashed line), B (intermediate radius, ejected mass and explosion energy; blue dashed line) and C (small radius, massive ejecta, high explosion energy; red dotted line) described in the text.

Table 4. Physical parameters of models A, B and C presented in Fig. 10 and described in more detail in the text.

Models	R_0 (10^{12} cm)	E_0 (10^{51} erg)	v_0 (km s^{-1})	$M_{\rm ej}$ (M$_\odot$)	$M_{\rm Ni}$ (M$_\odot$)
A	25 ± 7	0.5 ± 0.2	8000 ± 1000	0.6 ± 0.1	0.25 ± 0.05
B	4 ± 2	3.0 ± 0.5	$14\,000 \pm 1000$	1.0 ± 0.2	0.40 ± 0.05
C	1.5 ± 0.5	16 ± 5	$17\,000 \pm 1000$	4.5 ± 1.0	0.25 ± 0.05

span a wide range of values between 0.5 and 5 M$_\odot$. The progenitor star, at the time of its explosion, could have been even more massive than $\sim$7 M$_\odot$ (this is the pre-SN mass roughly derived adding the mass of the remnant to the ejected mass of model C, and it is remarkably similar to that adopted by Tominaga et al. 2007) because low-velocity material arising from a massive C–O mantle may well be present without significantly affecting the observed light curve.

Even though this preliminary data modelling cannot discriminate between high and low mass ejecta, the latter scenario seems inconsistent with other observational evidences. In particular, the observed major eruption preceding SN 2006jc (Pastorello et al. 2007a) and the large amount of material lost by the star before its core-collapse would suggest an originally very massive progenitor. Future, detailed light curve and spectral modelling accounting also for the effects of the ejecta–CSM interaction, would provide more robust constraints on the physical parameters of SN 2006jc and similar events.

5 PROGENITORS OF TYPE Ibn SUPERNOVAE

SN 2006jc has provided an excellent opportunity to study the nature of these objects, and to probe the nature of the progenitor stars. In Pastorello et al. (2007a) two different scenarios were discussed for the precursor star of SN 2006jc: a single WR star, originally very massive (up to 100 M$_\odot$) and, alternatively, a double system formed by an LBV (responsible for the 2004 outburst) and a canonical WR star which exploded to produce SN 2006jc. In the following we will analyse in more detail these two scenarios, extending the discussion to the precursors of all SNe Ibc.

5.1 Single massive progenitor scenario

A possible interpretation for the last period in the life of the progenitor of SN 2006jc is that an evolved WR star suffered a He-rich, luminous outburst in 2004 followed by the core-collapse two years later (Itagaki et al. 2006; Pastorello et al. 2007a). However, this sequence of events is at odds with our current understanding of the late stages of evolution of the most massive stars. For example, we have no evidence locally that evolved WR stars produce sporadic He-rich mass ejections. There may be some evidence of a link between Ofpe/WN9 stars and LBVs but such objects still retain a He- and H-dominated envelope. The progenitor of SN 2006jc is not likely to have been such a WN–LBV transition object when it underwent core-collapse, as there was no clear spectroscopic evidence of broad He I or H features which could be attributed to the high-velocity ejecta. The analysis of the spectral properties (Foley et al. 2007; Pastorello et al. 2007a) showed that the ejecta of SN 2006jc were rich in intermediate-mass elements like normal SNe Ic, and there was evidence of the presence of a slowly moving, He-rich CSM. Luminous outbursts, such as that observed in 2004 at $M_R \sim -14.1$ coincident with the position of SN 2006jc (UGC 4904−V1), are expected to be produced by proper LBV stars only (Davidson & Humphreys 1997) which are generally He- and H-rich, and indeed the outburst is accompanied by the ejection of a large fraction of the outer envelope (Humphreys, Davidson & Smith 1999). However, current stellar evolutionary theory would not predict that such η-Car type objects would undergo core-collapse so close (2 yr) to the LBV stage (Heger et al. 2003; Eldridge & Vink 2006). Instead, it would suggest a residual life time for the star of another 10 000–100 000 yr.

One would then be forced to conclude that the 2004 luminous outburst was produced by a WR star, which (almost) completely stripped its He envelope. The naked C–O WR star was still embedded in the He-rich CSM at the time of the core-collapse. Since similar narrow He I features were observed in the spectra of all SNe Ibn, we can reasonably conclude that all their WR precursor stars likely suffered similar dramatic mass-loss episodes shortly before their death as SNe. While we cannot completely exclude the presence of broad He I components in the spectra of SN 2006jc, there is unequivocal evidence of such broad features only in the early-time spectra of SN 2000er and in the mid-age spectra of SN 2002ao. In these SNe, the narrow (1000–2000 km s^{-1}) circumstellar He I lines are found atop the broad ($\sim$5000 km s^{-1}) He I components. This suggests that at least these two objects underwent core-collapse when the progenitor stars were in the transition between WN and WC phase (for details on the physical subclassification of WR stars, see e.g. Eldridge & Vink 2006; Crowther 2007).

Recently, Smith et al. (2007) and Langer et al. (2007) proposed that the bright Type IIn SN 2006gy (see also Ofek et al. 2007) might be a pair-creation SN (PCSN), an exotic event produced by the explosion of a very massive star (more than 100 M$_\odot$, Heger & Woosley 2002). Though some of the expected properties of PCSNe are consistent also with the observables of Type Ibn SNe (e.g. moderate to low metallicity of the host galaxies, slow observed spectral evolution, high peak luminosity, moderate expansion velocity of the ejecta), PCSNe are believed to produce a much larger amount of ^{56}Ni than observed in SN 2006jc and similar events.

An alternative scenario, in good agreement with the observed properties of SN 2006gy and the brightest interacting SNe, was presented by Woosley, Blinnikov & Heger (2007). Some of these luminous events might originate from the collision between shells of material ejected by very massive stars (originally in the range 100–130 M$_\odot$). The mechanism that leads to the ejection of many solar masses of the envelope, but not necessarily the explosion of the entire star, is the production of electron–positron pairs. After the first outburst, the stellar nucleus contracts, searching for a new phase of stable burning. A subsequent explosion may occur shortly after, ejecting several solar masses of material, which eventually collides with the material expelled in the previous outburst. According to Woosley et al. (2007), the luminosity of such events can be up to 10 times higher than that of a CC SN. After the entire H envelope is stripped away, also a sufficiently high mass of the remaining He core may generate multiple ejections of material (Woosley et al. 2007). In light of all of this, the progenitor of SN 2006jc might have had a similar fate, experiencing the last episode of such a sequence of luminous outbursts in 2004, followed by the core-collapse of the residual C–O core in 2006.

5.2 Binary (LBV + WR) scenario

Although the single, massive progenitor scenario may offer some compelling explanations for most of the observed SN properties, it is at odds with current evolutionary theories in which no major LBV-like outburst is expected from a WR star. Even more surprising is that it occurred so close in time (only 2 yr before) to the collapse of the stellar core. There is also no observational evidence that any WR-type star has ever undergone such a luminous outburst. All the bright outbursts from very massive stars have occurred in (He + H)-rich LBV stars (Humphreys et al. 1999). These outbursts are likely accompanied by an ejection of $\sim$10 M$_\odot$ of material (Smith et al. 2003), which is uncomfortably large to be consistent with an evolved WR progenitor.

An intriguing feature is the presence of a weak and narrow Hα ($v_{\rm FWHM} \sim$ 1000 km s^{-1}) in the late-time spectra of SN 2006jc (see Fig. 6 and Smith et al. 2008). This evidence, together with the detection of the luminous outburst in 2004 October, led us to propose an alternative scenario, i.e. a binary system composed of two massive stars at different evolutionary stages (Pastorello et al. 2007a). The pair could be formed by a typical LBV producing the 2004 transient and a more evolved WR star exploding as an SN. The LBV is losing its H envelope via recurrent outbursts like UGC 4904−V1, while the ejecta of SN 2006jc are colliding with the dense He-rich wind from the WR precursor star, possibly triggered by the binary interaction. Only once the SN ejecta reach the H-rich shell produced by the LBV, the narrow H emission lines become visible in the SN spectra. While the overall spectral evolution is similar in the Type Ibn SN group, there are significant differences in the strength of the Hα emission: it is clearly visible in the 1.5-month-old spectrum of SN 2002ao shown by Foley et al. (2007, see also our Fig. 7), very weak in SN 2006jc and undetected in SN 1999cq (Matheson et al. 2000) and in the very early spectra of SN 2000er. While the increasing strength of Hα in the spectra of SN 2002ao would suggest a scenario analogous to that of SN 2006jc, this is not necessarily true in the cases of SNe 1999cq and 2000er, which do not show any evidence of narrow H lines in their spectra.

The probability of discovering binary systems composed of massive stars evolving with the same time-scales might appear quite low. However, massive binary systems in which one component is a WR star are frequently found in the Galaxy and the Local Group. In fact, a system similar to the putative precursor binary producing SN 2006jc is well known in the Small Magellanic Cloud: HD5980 (Koenigsberger 2004, and references therein). The system consists of a primary massive star of about 50 M$_\odot$ suffering episodic LBV outbursts suggesting that the star is on its way to evolve into a He-rich WR star (Koenigsberger et al. 1994; Barba et al. 1995; Koenigsberger et al. 1995), and a more evolved eclipsing companion already beyond the LBV phase and identified as a $\sim$28 M$_\odot$ WR star (Koenigsberger, Kurucz & Georgiev 2002). The system might be even more complex, possibly hosting a third (O4-O6 type) star, gravitationally bound to the system but with a very long orbital period (Niemela 1988; Breysacher & Perrier 1991; Koenigsberger et al. 2002). However, binary systems consisting of a WR star with a massive companion which may span a large range of evolutionary stages (main-sequence O-type stars, red supergiants, LBVs or other WR stars) are quite common, e.g. systems with a WR plus a massive main-sequence O-type star (Setia Gunawan et al. 2001; Van den Hutch 2001), or WR binaries (Conti & Massey 1989; Foellmi, Moffat & Guerrero 2003a,b). Moreover, Eldridge (2007) found that very massive stars which are thought to produce Type Ic SNe are more likely to have a binary companion, possibly an LBV, than lower mass stars. In fact, assuming a flat secondary mass distribution, Eldridge (2007) estimated that 60 per cent of the companions of 200 $M_{\odot}$ primary SN precursors in binary systems are post-main-sequence objects, and therefore potentially LBVs. For a 100 $M_{\odot}$ star the percentage decreases to 40 per cent, while for a 50 $M_{\odot}$ star, it is only 20 per cent. With this evidence, an SN explosion of a WR star whose ejecta may at some stages collide with CSM released by the companion star might not be an unrealistic event.

6 FREQUENCY OF TYPE Ibn SUPERNOVAE

So far, only the four objects described in this paper (plus may be the transitional SN 2005la, Pastorello et al. 2008) can be properly classified as Type Ibn SNe. Since none were discovered before 1999, one may raise the question if these events are intrinsically rare or, perhaps, more common but misclassified in the past because of the inadequate spectral and photometric monitoring. Although these SNe have unique characteristics, we can suggest only one object discovered before 1999 that may have some observed properties in common with SNe Ibn: the historical SN 1885A.

6.1 The enigmatic SN 1885A (S Andromedae)

The light curve of SN 1885A (also known as variable S Andromedae) was characterized by a surprising, rapid rise to peak similar to that observed in SNe Ibn (see Fig. 11). This enigmatic SN event has been considered up to now as a peculiar 1991bg-like Type Ia SN (e.g. van den Bergh 1994). However, its light curve is different from that of any other SN Ia observed so far, having an asymmetric shape and an extremely fast post-max decline (Fig. 11). For the visual light curve of SN 1885A a $\Delta m_{15}(V) = 2.28$ mag was estimated by van den Bergh (2002). This is much more than the V-band post-maximum decline of the underluminous Type Ia SN 1998de ($\Delta m_{15}(V) = 1.31$ mag, Modjaz et al. 2001). Using a relationship between colour and decline rate for underluminous 1991bg-like SNe Ia (see also Garnavich et al. 2004), van den Bergh (2002) obtained a value of $\Delta m_{15}(B) = 2.21$ mag, which is not only inconsistent with that of a normal SN Ia, but also much higher than any 1991bg-like event observed so far, being in the range between 1.6 and 2 (Garnavich et al. 2004; Taubenberger et al. 2007). In addition, even with negligible extinction, SN 1885A is more luminous than the 1991bg-like SNe (see e.g. SN 1998de in Fig. 11; Modjaz et al. 2001; Jha et al. 2006). Some observed characteristics of the light curve of SN 1885A mimic those of SN 2006jc and similar objects, although its peak luminosity is probably lower than those of the four events discussed here. However, the host galaxy reddening

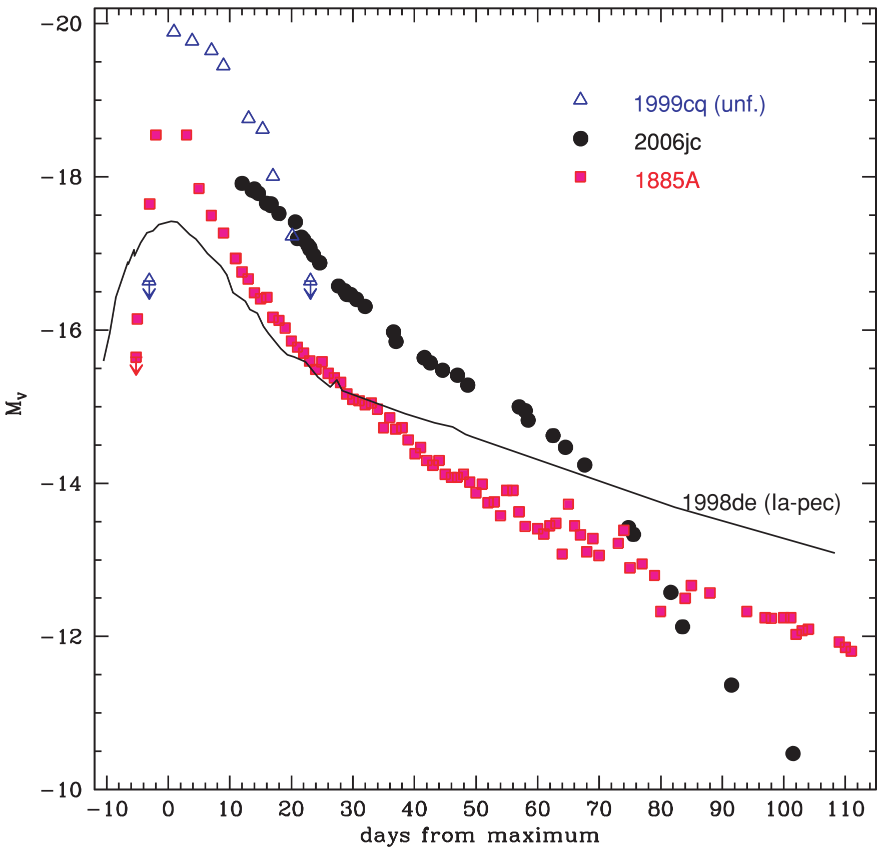

Figure 11. *V*-band absolute light curve of SN 1885A (de Vaucouleurs & Corwin 1985) compared with those of SN 2006jc and the low-luminosity SN Ia 1998de (Modjaz et al. 2001; Jha et al. 2006). The early, unfiltered light curve of 1999cq (Matheson et al. 2000) is also shown.

is poorly known, and a significant internal extinction would make SN 1885A brighter and bluer. The pre-maximum rise of its light curve is extremely fast: the SN brightened by 3 mag in 3–4 d (van den Bergh 2002). Such a fast luminosity evolution is comparable to that of the SNe of our sample, as tentatively determined from the epochs of pre-discovery limits and the earliest detections.

So, can SN 1885A be considered as a nearby, historical analogue of SN 2006jc? There is some other evidence that might favour this scenario. A historical spectrum of SN 1885A is described by de Vaucouleurs & Corwin (1985, and references therein). The spectrum shows a continuum (blue, according to Sherman 1886) with possible absorption features at about 4500 and 5700 Å, and several bright bumps that have been interpreted as emission features. In particular the strongest of them is at about 5880 Å which was noted in all historical observations reported by de Vaucouleurs & Corwin (1985). This is quite consistent with the He I 5876 Å emission. Moreover, Branch (1987) classified SN 1885A as a peculiar Type I SN (possibly of Type Ib) remarking on the absence of prominent absorption features at about 6150 Å. Hence the Si II 6355 Å absorption component typical of SNe Ia is probably missing.

Despite this, a number of papers describing ground based and *Hubble Space Telescope* narrow-band imaging of the SN remnant (Fesen, Saken & Hamilton 1989; Fesen et al. 1999; Hamilton & Fesen 2000; Fesen et al. 2007) argue in favour of a Type Ia nature for SN 1885A. All these studies show the remnant of SN 1885A to have spherical symmetry and to be detected in absorption against the luminous bulge of the host galaxy (M31), because of the prominent Ca I, Ca II, Fe I and Fe II absorption lines characterizing the remnant. Abundance arguments, the symmetric shape of the remnant and the lack of major star formation in the bulge of M31 would all support a thermonuclear explosion scenario. However, the abundances predicted in these papers and the moderate ejected ^{56}Ni mass (Fesen et al. 2007) are not inconsistent with those of luminous H-deprived core-collapse SNe. There is some evidence that massive stars which explode as core-collapse SNe may sometimes be hosted in SO and early spiral galaxies, like the extremely luminous SN 2006gy (Smith et al. 2007) and the ultrafaint SN IIP M85-OT2006 (Pastorello et al. 2007b), although we would admit that the true nature of these transients is currently being debated (Kulkarni et al. 2007; Ofek et al. 2007; Rau et al. 2007). Despite the decades of studies of SN 1885A, the real nature of this event still remains a puzzle.

6.2 Type Ibn SN rate

Some basic properties of SN progenitors (such as their interval of initial mass) can be estimated through the measurement of the local SN rates (e.g. Cappellaro et al. 1997; Cappellaro, Evans & Turatto 1999; Mannucci et al. 2005; Mannucci, Della Valle & Panagia 2006; Botticella et al. 2008). The measurement of the SN rate is based on the 'control time' methodology, developed by Zwicky in the 1930s which requires intensive observational campaigns on selected galaxies and the use of light-curve templates for each SN type. For the case of SNe Ibn the estimate of their frequency of occurrence is complicated by the fact that the total amount of the control time is not accessible and the available statistics are made up of just a handful of objects. However, we can attempt to get around these drawbacks by assuming that all galaxies within a given volume have been monitored consistently and with similar control times. If this is assumed true, a rough estimate of the rate of SNe Ibn can be derived after rescaling the rate of core-collapse SNe (CC SNe) (expressed in terms of SNuB or SNuM[3]) with the ratio (SNe Ibn)/(CC SNe). The distance limit has been set after comparing the cumulative frequencies of the distribution of core-collapse SNe and SNe Ibn, which result to be statistically indistinguishable within $cz \sim 10\,000$ km s^{-1} (see Fig. 12, Kolmogorov–Smirnov probability $P = 0.74$). We also note that the first SN which can be properly classified as a Type Ibn event has been discovered in 1999. Though intrinsically rare, it is very likely that some other SNe Ibn might have occurred before 1999, but probably misclassified, due to poor spectroscopic follow-up, as Type IIn or Ib/c events (or even as peculiar Type Ia SNe, see Section 6.1). Therefore a temporal cut-off around 1999 has been applied to the upgraded version of the Asiago SN catalogue[4] (see also Barbon et al. 1999). Our analysis finds that, after 1999, 700 SNe have been classified as Type II or Ib/c SNe within $cz = 10\,000$ km s^{-1}. From this, and considering also the transitional SN 2005la (Pastorello et al. 2008) as a Type Ibn SN event, we derive a ratio (SNe Ibn)/(CC SNe) $\sim 10^{-2}$ which corresponds to 0.005–0.01 SNuB and 0.002–0.008 SNuM after assuming an average Hubble type for the parent galaxies of SNe Ibn ranging from Sa to Scd (see column 5 in Table 1).

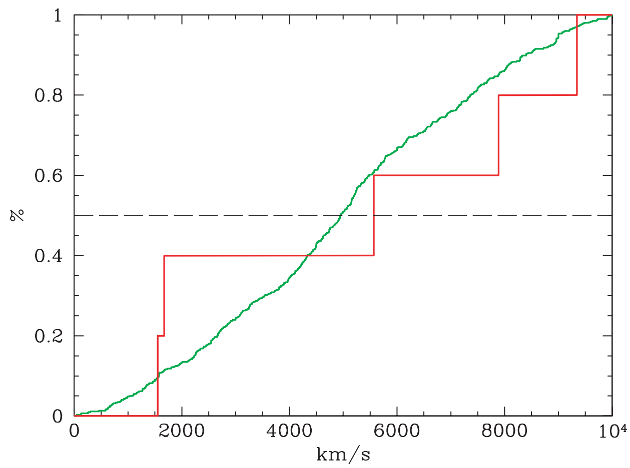

Figure 12. Cumulative distribution of the radial velocities of the host galaxies of all CC SN types (green line) and Type Ibn SNe only (red line), within $cz \sim 10\,000$ km s^{-1}, as derived from the Asiago Supernova Catalogue.

These values are remarkably consistent with the ratio (SNe Ibn)/(CC SNe) derived taking into account all the nearby ($v_{\rm rec} \leq 2000$ km s^{-1}) core-collapse SN events discovered during the period 1999–2006. With a total sample of 76 core-collapse SNe, Smartt et al. (in preparation) found (SNe Ibn)/(CC SNe) $\approx 2.5 \times 10^{-2}$.

7 SUMMARY

We have presented new data for three Type Ibn SNe, i.e. SN 2000er, SN 2002ao and SN 2006jc. In particular, the early-time data of SN 2000er show, for the first time, the early spectroscopic behaviour of a Type Ibn event. Early-time spectra of SN 2000er show relatively broad wings in the He I lines, with additional much narrower components. The detection of broad He I spectral features is unequivocal evidence for the presence of He also in the SN ejecta, not only in the CSM. Therefore, a residual envelope of He might be present in the

[3] SNuB is the number of SNe per century per 10^{10} L$_\odot$ in the *B* band, while SNuM is the number of SNe per century per 10^{10} M$_\odot$ of stellar mass.
[4] http://web.oapd.inaf.it/supern/cat/.

progenitors of some SNe Ibn. Finally, the very late spectra of SN 2006jc still show strong narrow circumstellar He I lines, together with an emerging Hα likely produced in another CSM region.

This data set allows us to highlight some key points concerning this new class of SNe, since we have now a better picture of the overall spectrophotometric evolution of SNe Ibn, which is essential to better constrain the characteristics of this class: (i) SNe Ibn show a surprisingly high degree of homogeneity, which is unexpected if the ejecta were strongly interacting with surrounding CSM; (ii) the modelling of the bolometric light curve of SN 2006jc (assuming no ejecta–CSM interaction) suggests that an amount of 0.2–0.4 $M_{\odot}$ of ^{56}Ni was ejected. The mass of ^{56}Ni could even be slightly higher for the brightest SNe Ibn (e.g. SN 1999cq). However, we cannot exclude that the interaction between SN ejecta and CSM may power the light curves of SNe Ibn to some degree, hence the ^{56}Ni mass might be somewhat lower; (iii) the observed data can be modelled without invoking extraordinarily massive ejecta; (iv) their intrinsic rarity (being $\sim$1 per cent of all core-collapse SNe) is probably due to the fact that they arise from a rather exotic progenitor scenario, consistent with either a post-LBV/early-WR channel of a very massive (60–100 $M_{\odot}$) star, or a binary (or even multiple) system formed by a normal LBV plus a core-collapsing WR companion.

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